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Coronary CT in Patients with a History of PCI or CABG: Helpful or Harmful?

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Abstract

Purpose of Review The purpose of this review is to evaluate the role of coronary computed tomography angiography (CCTA) in the assessment of patients after coronary artery bypass graft surgery (CABG) or percutaneous coronary intervention (PCI).

Recent Findings Advances in CT technology have resulted in tremendous improvements in diagnostic performance, safety, and ease of performance. CCTA accurately detects graft stenosis or occlusion. However, assessment of native coronary arteries in patients after CABG is challenging due to commonly present severe coronary calcifications. CCTA evaluation of coronary stents using contemporary technology allows for exclusion of in-stent restenosis in suitable patients with larger stents (diameter ≥ 3 mm). Recent studies show promising results for assessment of smaller stents (diameter < 3 mm).

Summary CCTA is a non-invasive, low-risk, and lower-cost alternative to invasive coronary angiography (ICA) for evaluation of patients after CABG or stents. Combining CCTA with myocardial CT perfusion or CT-based fractional flow reserve as well as photon-counting CT may expand its role for assessment of these patients.

Keywords Coronary computed tomography angiography · Coronary artery bypass grafting · Percutaneous coronary intervention · In-stent restenosis

Introduction

In the USA, more than a million patients with coronary artery disease (CAD) undergo percutaneous coronary intervention (PCI) or coronary artery bypass graft surgery (CABG) each year [1]. Benefits of revascularization include reduced angina pectoris, improved ventricular function, and longer overall survival. However, a proportion of patients will develop recurrent symptoms because of failure of the grafts, in-stent restenosis, or progression of CAD elsewhere.

After CABG, the prevalence of angina pectoris after 1 year is 20–30%, increasing to 40–50% after 6 years [2, 3]. Graft failure occurs in a substantial proportion of CABG conduits. Mechanisms leading to graft failure include technical issues, acute thrombosis, neo-intimal hyperplasia, and accelerated atherosclerosis [4, 5]. The incidence of graft failure varies depending on biological mechanisms, target vessel characteristics, surgical technique, and type of graft used. The patency rate at 10 years ranges from 50 to 60% for venous grafts, 85 to 95% in internal mammary artery grafts, and 89 to 91% for radial artery grafts [5]. In addition to graft failure, recurrent angina may be caused by progression of atherosclerotic disease in the native coronary arteries. Therefore, evaluation of patients with bypass grafts should not be limited to the surgical conduits alone, particularly for patients presenting with symptoms long after surgery [6, 7].

After PCI recurrent angina may be caused by in-stent restenosis in the form of neo-intimal hyperplasia or thrombosis, but

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symptoms may also result from progression of disease elsewhere. Neo-intimal hyperplasia as a reaction to injury of the arterial wall generally develops gradually over time causing stable angina symptoms, but may also present as myocardial infarction [8, 9]. The introduction of drug-eluting stents (DES) represented an important milestone in coronary intervention, significantly lowering the need for re-intervention compared with bare metal stents [10–12], Nevertheless, in-stent restenosis is still encountered in a substantial number of patients after PCI with DES. Predictors of restenosis include small vessel size, increased stented length, complex lesion morphology, diabetes mellitus, and prior bypass surgery [13].

Invasive coronary angiography (ICA) remains the reference standard for evaluating the patency of coronary bypass grafts and coronary stents. Because ICA is an invasive procedure with a small risk for serious complications [14], non-invasive stress tests are commonly performed to assess inducible myocardial ischemia. However, several studies have shown that the performance of various stress tests is lower after myocardial revascularization [15, 16]. Over the past decades, non-invasive coronary angiography using electrocardiography (ECG)-synchronized multidetector computed tomography (CT) has emerged as a valuable diagnostic tool in the management of patients with suspected CAD. Both for patients with chronic and acute chest pain, coronary CT angiography (CCTA) provides an alternative to stress tests to reliably rule out CAD, expedites care, and optimizes preventive management [17–20]. Although not investigated as extensively, CCTA may be valuable in the management of patients with established CAD and prior myocardial revascularization.

Assessment of Bypass Grafts Using CT

Compared to the coronary arteries, coronary artery bypass grafts have larger luminal diameters, less calcifications and remain relatively stationary during cardiac contraction (Fig. 1). These properties enable cardiac CT to assess grafts more accurately compared to the small and tortuous coronary arteries [21]. A specific challenge to the interpretation of bypass grafts is the presence of metal objects in the form of vascular clips, sternal wires, and surgical material used at the ostium of the graft at the aortic root, which cause beam hardening (Fig. 2a) and partial volume artifacts and limit interpretation of vascular structures in their proximity [22–24].

Although early attempts with single-slice CT scanners demonstrated that graft patency could be assessed non-invasively, the first multislice CT systems with 4–8 detector rows for the first time allowed for visualization of entire bypass grafts and detection of stenosed or occluded grafts. Despite promising initial results, the number of non-interpretable grafts was high (38%), often due to metal artifacts [25]. The number of unevaluable grafts decreased after the introduction of 16–64-slice systems, which had better spatial and temporal resolution, as well as extended longitudinal coverage. Hamon et al. pooled the results of 15 studies, including 723 patients and 2023 grafts, using 16- and 64-slice spiral CT technology for the assessment of grafts [22]. The diagnostic accuracy was high with a sensitivity of 98% (95% confidence interval (CI) 96–99%) and a specificity of 97% (95% CI 96–98%) for detecting graft occlusion or significant stenosis (> 50%); however, 8% of grafts were not fully assessable mainly due to cardiac motion, respiratory artifacts, poor opacification, and the presence of surgical clips [22].

Several meta-analyses investigated the diagnostic performance of CT systems with 64 slices or more [26–28], demonstrating a good diagnostic performance when compared to ICA. The largest and most recent meta-analysis, published by Chan et al., included 31 studies with 1975 patients and 5364 grafts that assessed the diagnostic performance of 64-slice CT and upward against ICA. They reported a sensitivity of 96% (95% CI 94–97%) and specificity of 96% (95% CI

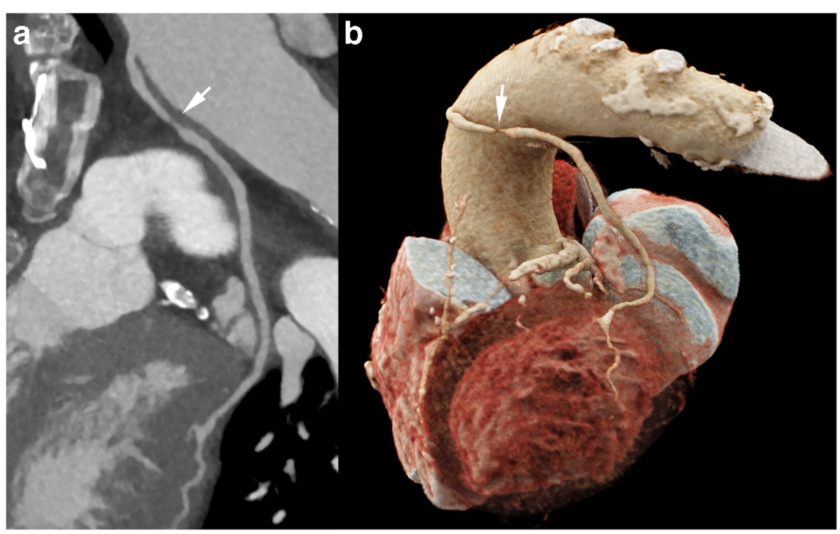

Fig. 1 Curved multiplanar reformation (**a**) and cinematic 3D rendering (**b**) of a patient after CABG demonstrating significant stenosis in a vein graft (arrow)

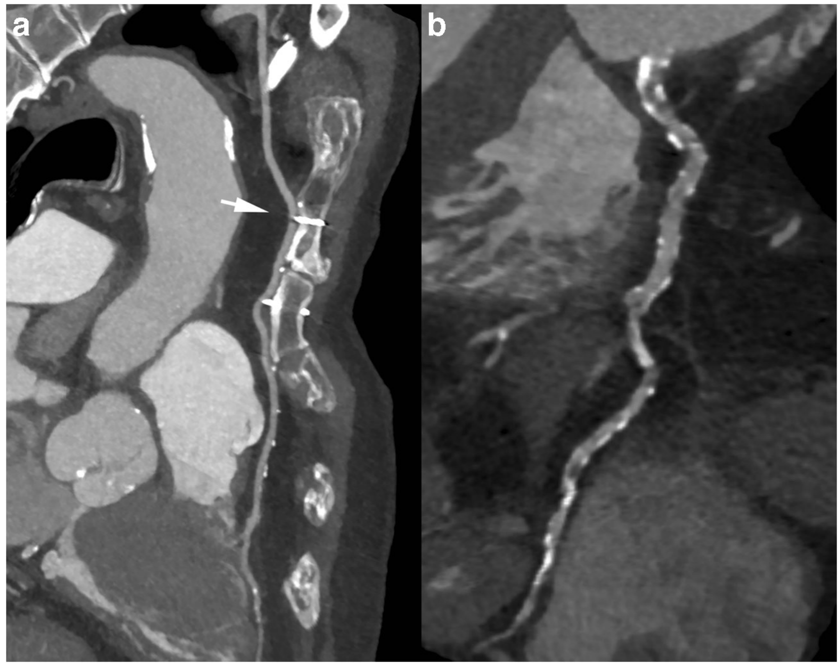

Fig. 2 Curved multiplanar reformations of a left internal mammary artery graft with a course in close approximation to the sternum (**a**); the location of grafts are important if redo CABG is indicated. Beam hardening artifacts is caused by sternal wires (arrow). The native left anterior descending coronary artery shows diffuse calcifications (**b**), which limits the evaluation of this artery

95–97%) for the detection of graft stenosis or occlusion. The sensitivity of CT was higher for venous graft disease compared to arterial grafts, while specificity was comparable between both graft types. A sub-analysis showed that sensitivity and specificity were similar between dual energy CT and conventional CT [27•]. Since publication of these meta-analyses, several validation studies have been performed using more contemporary CT equipment (Table 1) [29–32]. Yuceler et al. investigated the performance of dual-source CT (128 slices) in 88 patients with 215 grafts and 645 graft segments using an ECG-triggered high-pitch spiral scan mode. The image quality was excellent in 92% of the grafts. Sensitivity and specificity for assessing graft patency were 97% and 100%, respectively, and for identifying luminal stenosis 93% and 100%, respectively. A trend towards better image quality was demonstrated among patients with lower heart rates [30]. De Graaf et al. investigated the performance of a 320 detector row CT system in 40 patients with 89 grafts (28 arterial grafts and 61 venous grafts). Sensitivity and specificity for detection of significant stenosis were 96% and 92%, respectively. All 23 occluded grafts were correctly identified with CT while 4 grafts (specificity = 94%) where incorrectly identified as occluded [32].

Recent advances in CT technology have resulted in a substantial reduction of radiation dose associated with imaging of bypass grafts using CT. Chan et al. reported a mean radiation dose ranging from 2.2 to 30 mSv in their meta-analysis of CT with 64 slices or more [27•]. Studies evaluating > 64-slice CT systems resulted in lower effective radiation doses (1.8–7.8 mSv) compared to 64-slice CT systems (6.5–30 mSv) [29, 30, 32]. The effective radiation dose was lower in patients with lower heart rates and lower body mass indices [29, 30].

Assessment of Native Coronary Arteries

The diagnostic work-up of patients with recurrent angina after CABG is challenging and should include assessment of bypass grafts, native non-grafted arteries, as well as distal post anastomotic coronary arteries. Evaluation of native coronary

Table 1 Diagnostic performance of contemporary CT technology for coronary artery bypass graft evaluation

Author	Year	CT technology	Cases (*n*)	Grafts	Arterial/venous grafts (*n*)	Se (%)	Sp (%)	PPV (%)	NPV (%)	Radiation dose
Koplay [29]	2016	128-slice DSCT	45	110	40/70	90	99	90	99	1.83 ± 0.89 mSv
Yuceler [30]	2014	128-slice DSCT	88	215	93/122	93	100	87	100	2.5 ± 0.6 mSv
Chaosuwannakit [31]	2014	128- slice DSCT	54	164	52/112	100	98	91	100	Not reported
De Graaf [32]	2011	320-slice SSCT	38	89	28/61	96	92	83	98	7.8 ± 3.3 mSv

DSCT dual source computed tomography, *SSCT* single source CT, *Se* sensitivity, *Sp* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *mSv* millisievert arteries by CT can be challenging in patients with bypass grafts since advanced atherosclerosis is prevalent, often resulting in extensive vascular calcifications and diffuse narrowing of the vessel lumen (Fig. 2b) [32–39]. Studies with 4- and 16-slice CT showed that 66–69% of coronary segments were evaluable after CABG. For the detection of significant stenosis, the sensitivity was 79–92% and the specificity 72–77% [24, 40]. Table 2 lists studies which investigated the accuracy of 64-slice CT systems and beyond in comparison to ICA for the evaluation of native coronary arteries in patients after CABG [32–39]. The sensitivity and specificity for detecting relevant stenosis were 83–100% and 77–100%, respectively, whereas the positive predictive values ranged from 67 to 100% and the negative predictive values from 83 to 100%. Most of these studies excluded vessel segments with diameters of less than 1.5 mm. De Graaf et al. analyzed all vessels of 40 patients using 320-slice CT, including those with diameters of less than 1.5 mm. Seven percent of the recipient vessels and 4% of the non-grafted vessels were of non-diagnostic image quality. Sensitivity and specificity for detection of significant stenosis in recipient vessels were 88% and 89%, respectively, which was lower for detection of significant stenosis in non-grafted vessels (sensitivity 83% and specificity 77%) [32]. Weustink et al. studied the diagnostic performance of dual-source 64-slice CTA in 52 patients with 289 grafted vessel segments and 118 non-grafted vessel segments [33]. A segment-by-segment analysis showed a sensitivity and specificity for detection of significant stenosis in recipient vessels of 100% and 96%, respectively. For detection of significant stenosis in non-grafted vessels, the numbers were 97% and 92%, respectively. Segments with coronary diameters < 1.5 mm were excluded from this analysis and the diagnostic performance of CTA in this study was lower in patients with heart rates ≥ 65 beats per minute compared to patients with heart rates < 65 beats per minute.

In addition to the patency assessment of grafts and native coronary arteries, cardiac CT may provide additional important information for evaluation of CABG patients. Several studies have shown that CCTA can predict prognosis in CABG patients. Chow et al. studied 250 CABG patients who underwent CCTA and found that the number of unprotected coronary territories was associated with major cardiovascular events [41]. In a larger cohort with longer follow-up, Mushtaq and colleagues evaluated cardiac CT exams of 698 patients who underwent CABG and showed that cardiac CT may be a promising tool for long-term risk stratification by identifying unprotected coronary territories [42]. The coronary artery protection score combines the atherosclerosis severity in the native coronary arteries as well as the grafts. Small et al. found that CCTA derived coronary artery protection score can predict all-cause mortality in CABG patients. This CTA derived score was able to appropriately reclassify 27% of patients, with incremental value over clinical characteristics [43].

Another potential benefit of cardiac CT is the possibility for evaluation of patients with an unknown number and position

Table 2 Diagnostic performance of ≥ 64-slice CT systems for native coronary artery evaluation after CABG

Author	Year	CT technology	Cases (n)	Native coronary artery segments (n)	Se (%)	Sp (%)	PPV (%)	NPV (%)
Ropers [39]	2006	64-slice SSCT	50	621	86	76	44	96
Onuma [37]	2007	64-slice SSCT	53	685	94	88	84	95
Nazeri [36]	2009	64-slice SSCT	98	1183	93	88	74	97
Weustink [33]	2009	64-slice DSCT	52	558	95[a] 97[b] 100[c]	100[a] 92[b] 96 [c]	100[a] 83[b] 97 [c]	99[a] 99[b] 100 [c]
Andreini [35]	2010	64-slice SSCT	119	277	91[d] 100[e] 100f	99 99 98	91 96 94	99 100 100
Romagnoli [34]	2010	64-slice SSCT	77	226	95 [a]	97 [a]	NA	NA
De Graaf [32]	2011	320-slice SSCT	40	127	83[b] 88[a]	77[b] 89[a]	77[b] 67[a]	83[b] 97[a]
Sahiner [38]	2012	64-slice DSCT	284	1020	98[b]	99[b]	96[b]	100[b]

DSCT dual-source CT, *SSCT* single source CT, *Se* sensitivity, *Sp* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *NA* not available

[a] Analysis of distal runoffs segments

[b] Analysis of non-grafted segments

[c] Analysis of grafted segments

[d] Prospective ECG gated (body mass index-adjusted tube voltage)

[e] Prospective ECG gated (120 kV)

[f] Retrospective ECG gate

of grafts [44]. Understanding the anatomy of grafts before ICA may shorten procedure duration and reduce radiation dose as well as volume of iodinated contrast. Finally, cardiac CT may also benefit assessment of redo CABG candidates, by providing information regarding the location of patent grafts and other structures in relation to the sternum. This information may reduce complications from re-thoracotomy (Fig. 2a).

Future Opportunities

Patients who underwent CABG commonly have diffuse coronary artery disease and multiple angiographic stenosis of uncertain hemodynamic consequences. Occluded grafts do not necessarily cause myocardial ischemia depending on the extent of collateral vascularization and myocardial viability. Perhaps even more so than in non-CABG patients, the detection of myocardial ischemia and viability is essential to determine the need for revascularization. In addition to improvements in the morphological assessment of CTA, future research may focus on hybrid imaging combining anatomical and functional imaging in order to detect stenosis related ischemia and to improve the risk stratification after CABG surgery. There are different methods to detect myocardial ischemia using nuclear imaging, stress echocardiography, or MRI. Kawai et al. showed that the combination of CCTA and stress-rest myocardial perfusion imaging using SPECT improves the predictive accuracy of cardiac events in patients after CABG [45]. In addition to these established techniques, it is also possible to perform myocardial perfusion imaging using CT. The CORE320 study compared the combination of CTA and static CT myocardial perfusion with ICA and SPECT perfusion imaging and found equivalent prediction of 2-year major adverse cardiovascular events-free survival, including the need for myocardial revascularization procedures [46]. Several other studies have demonstrated incremental diagnostic accuracy of static and dynamic CT perfusion imaging over CTA alone for the detection of hemodynamically relevant CAD. The ability to differentiate functionally relevant stenosis and occlusions with the use of CT perfusion imaging may be particularly useful in post-CABG patients but has not been prospectively investigated yet. Using computational fluid dynamics, it is now possible to model the functional relevance of coronary artery disease from anatomical images. CT-based fractional flow reserve (CT-FFR) only requires a resting CT angiogram to calculate the FFR throughout the coronary artery tree, which was shown to be at least as accurate as other stress imaging techniques, for the detection of functionally relevant coronary lesions as determined by invasive FFR [47]. CT-FFR has incremental value over CTA, improves clinical decision-making [48–50], and reduces the number of negative ICAs [51]. Although currently available, CT-FFR applications do not allow for evaluation of coronary grafts, dedicated algorithms may be developed for the assessment of CABG patients in the future.

Assessment of Coronary Stents

Despite the tremendous advances in CT technology, the evaluation of coronary stents remains challenging due to artifacts caused by the metal alloys. Stent artifacts are more relevant in devices with smaller diameters, thicker struts, and alloys containing heavier elements (gold, tantalum) (Fig. 3) [52]. Newer stents have thinner struts resulting in less artifacts (Fig. 4), whereas non-metallic stents like bio-absorbable stents can be imaged without interference (Figs. 5 and 6) [53, 54].

Three types of artifacts complicate imaging of coronary stents: (1) blooming artifacts, (2) beam hardening artifacts, and (3) motion artifacts. Blooming artifacts occur when tissues with widely different x-ray absorption behavior are encompassed on the same CT voxel. This produces average attenuation of these tissues in this voxel. Blooming artifacts cause stent struts to appear larger than they are, thereby impairing assessment of the stent's lumen. The severity of blooming artifacts depends on the stent architecture, stent diameter, stent strut thickness, and material composition as well as the spatial resolution and reconstruction methods of the scan [55–58]. Blooming artifacts have been partly solved by increasing spatial resolution, for example by using CT scanners with smaller detector elements. Beam hardening artifacts occur because the metal of the stent struts absorbs more of the lower-energy portion of the x-ray beam than the surrounding soft tissues, which results in dark areas (shadows) behind high-density structures. Beam hardening artifacts can be reduced by increasing the x-ray tube voltage, dual energy CT, and in the future by photon-counting CT [59]. Motion artifacts are the most common reason for non-assessable stents as they tend to exacerbate other kinds of artifacts [55]. The use of high gantry rotation speeds, multisegmental reconstruction techniques, and β-blockers to lower the heart rate consistently improves the interpretability of CCTA images.

Earlier generations of multidetector CT (4–16 rows) lacked temporal and spatial resolution for consistent visualization of the in-stent lumen [60, 61]. The improvement in the performance of CT scanners following the introduction of 64-slice CT resulted in a better diagnostic accuracy as it was shown in three meta-analyses [62, 63, 64•]. The percentage of assessable stents ranged from 89 to 91%, sensitivity for detection of intracoronary stent restenosis ranged from 90 to 93%, and specificity from 86 to 91% after the exclusion of non-assessable stents. The stent diameter is an important determent of the diagnostic accuracy in 64-slice CT, as a better diagnostic accuracy was achieved for assessment of stents with diameters ≥ 3 mm when compared to stents with diameters < 3 mm [62, 63, 64•]. De Graaf et al. compared the performance of

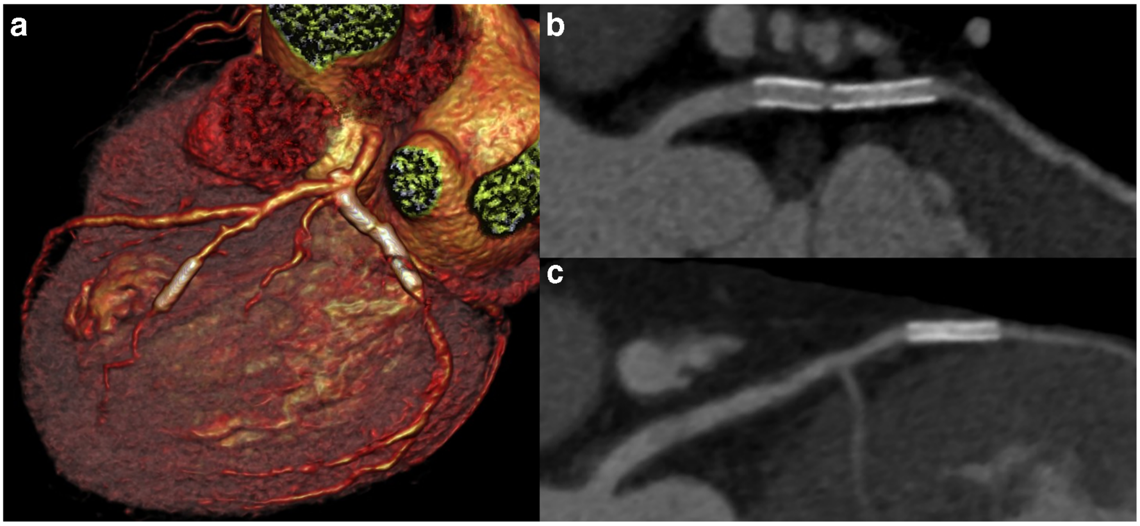

Fig. 3 3D volumetric reconstruction (**a**) and curved multiplanar reconstructions (**b**, **c**) after undergoing PCI. Two stents were placed in the circumflex coronary artery (**b**) and one stent in a diagonal branch (**c**). The two stents in the circumflex coronary artery have a larger diameter and therefore can be better evaluated compared to the stent in the diagonal branch, which has a smaller diameter. Restenosis cannot be ruled out confidently for the stent in the diagonal branch

320-slice CCTA with invasive angiography and also found the stent diameter to be an important predictor of image quality and diagnostic accuracy. In this study, 8% of stents were non-evaluable and the sensitivity, specificity, PPV, and NPV for the detection of in-stent restenosis were 92%, 83%, 46%, and 98%, respectively. Still, stents with a large diameter (> 3 mm) and thin struts (< 140 μm) allowed better in-stent visualization than stents with a small diameter or thick struts [65].

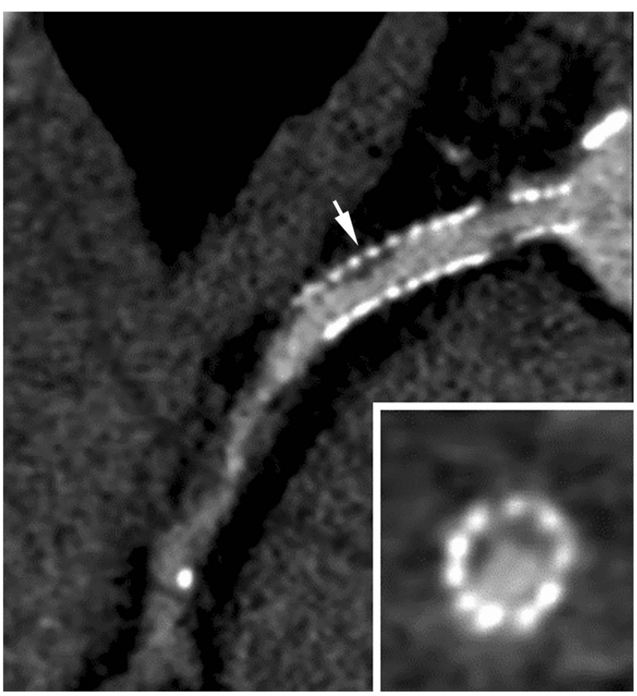

Fig. 4 CCTA of a patient after PCI with placement of two large stents in the right coronary artery. Neo-intimal hyperplasia without significant obstruction can be accurately assessed due to the large size of this stent and other favorable scan conditions (arrow)

Dual-source CT (DSCT) has a high fundamental temporal resolution. Liu et al. analyzed 13 studies using DSCT with 894 patients and 1418 stents [64•]. The number of assessable stents ranged from 89 to 100% with the overall percentage of 98% (1384 of 1418). The sensitivity and specificity for the detection of in-stent restenosis was 92% (95% CI 87.0–96.0%) and 91% (95% CI 87%–94%), respectively. Also in this analysis, the performance of DSCT was significantly better in stents with diameters ≥ 3 mm compared to stents with diameters < 3 mm. Third-generation DSCT scanners are equipped with an integrated circuit detector, which allows for a higher spatial resolution in the z-direction (through-plane resolution) and lower image noise [83]. Li et al. investigated the diagnostic performance of low radiation dose stent imaging in 69 patients using third-generation DSCT and found that small-caliber (< 3 mm) stents could not be assessed in 8.2% of cases, while all stents in the

Fig. 5 Patient with a bio-absorbable coronary scaffold. The properties of this device allow for reliable assessment of coronary artery patency by CCTA. Two small platinum pellets indicate the proximal and distal edges of the scaffold (arrows)

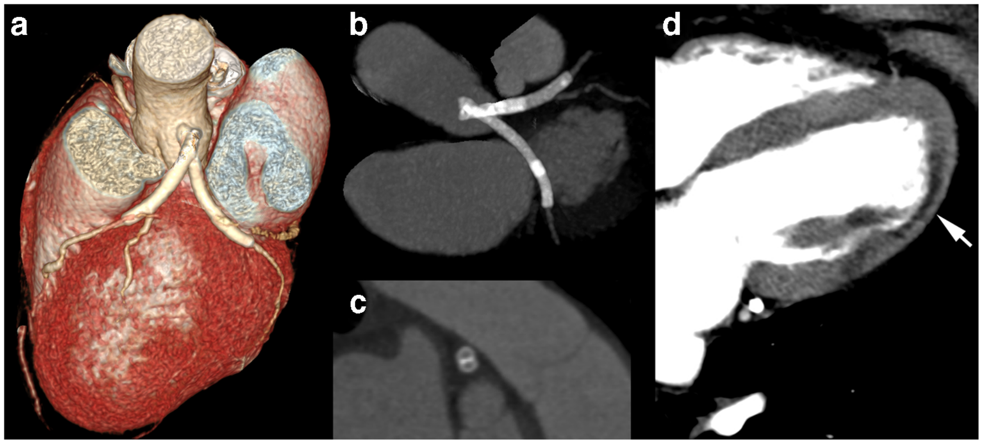

Fig. 6 Patient after PCI with two stents in the left main coronary artery. One stent extends into the left anterior descending coronary artery and the other extends into the circumflex coronary artery (**a**). The trajectory of the two stents can be evaluated well in a maximum intensity projection (**b**). A cross-sectional view shows both stents side-by-side in the left main coronary artery (**c**). An old myocardial infarction can be seen as a hypodense region in the left ventricular antero-lateral wall (arrows) (**d**)

large caliber (≥ 3 mm) group were assessable. The sensitivity, specificity, PPV, and NPV for detection of in-stent restenosis were 100%, 98%, 96%, and 100%, respectively in the large caliber stent group, while in the small-caliber group these values were 100%, 85%, 68%, and 100%, respectively. This difference was mainly due the non-assessable stents in the small-caliber group, which resulted in a relatively low specificity and PPV. Most of the small-caliber stents were 2.5 mm and 2.75 mm; therefore, the diagnostic performance of CCTA for 2.25 mm stents remains uncertain and needs to be validated by further studies [67••].

Andreini and colleagues recently investigated the diagnostic performance of new wide-array scanner [68] that combines better spatial resolution, iterative reconstruction algorithm, and an intra-cycle motion-correction algorithm. The cohort of 100 patients (192 stents) included patients with atrial fibrillation (13%), higher heart rates (26% > 65/min), and small stents (37% < 3 mm) in an effort to represent real world population. The results were promising as 97% of large stents and 92% of small-caliber stents were evaluable. The sensitivity, specificity, PPV, and NPV for detection of in-stent restenosis in the large caliber group were 92%, 96%, 75%, and 99%, respectively. In the small-caliber group, these numbers were 90%, 80%, 48%, and 98%, respectively. As in previous studies, the number of 2.25 mm stents was very small (2 patients) and most of the stents in the small-caliber group had a diameter of 2.75 mm. Despite the low number of very small stents and potential selection bias in these studies, the results indicate contemporary CT scanners may be better able to detect in-stent restenosis in smaller stents.

Future Opportunities

Post-PCI patients often have diffuse coronary artery disease and the assessment of the functional significance of coronary lesions is important for decision-making. Stress myocardial computed tomography perfusion (CTP) has recently emerged as a promising strategy to combine anatomical and functional evaluation during a single examination and recent studies have shown improved diagnostic performance for the diagnosis of hemodynamically significant coronary artery stenosis [69–72]. One study evaluated the additional diagnostic value of CT perfusion imaging for coronary stents [73] and showed that the sensitivity to detect in-stent restenosis increased from 56 to 78% ($p = 0.13$) and specificity from 78 to 90% ($p < 0.001$) when static CT perfusion was added to CCTA. The combination of functional and anatomical imaging by CT for patients with coronary stents may be valuable for decision-making regarding revascularization; however, it needs to be validated in future studies. Results of the multicenter ADVANTAGE study, which prospectively investigates the incremental diagnostic value of static CT perfusion imaging in patients with coronary stents to identify hemodynamically relevant obstruction, are expected in the near future [74].

The transluminal attenuation gradient is the average contrast opacification drop-off along the course of a coronary artery at CCTA. This gradient may provide information regarding blood flow in a vessel and improve the diagnostic accuracy of CCTA. In a study that included 52 patients and 104 coronary arteries, Chow et al. showed that contrast opacification drop-off across a stenosis at CCTA correlates with thrombolysis in myocardial infarction flow grade < 3 [75]. This was confirmed by Choi et al. who found that adding transluminal attenuation gradient to the interpretation of CCTA improved the diagnostic accuracy, especially for severely calcified lesions [76]. Dowsley et al. investigated the role of corrected coronary opacification differences in the assessment of coronary stents in a proof of concept study. They included 25 patients with 29 stented coronary arteries and demonstrated that adding corrected coronary opacification differences to CCTA improves the diagnostic accuracy for identifying significant stenosis and abnormal resting blood flow [77••]. Despite the promising results of this study, larger studies are needed before routine clinical use for the assessment of coronary stents. The use of CT-FFR for functional assessment of in-stent restenosis is currently limited as blooming artifacts caused by the stent metal struts make it difficult to apply this technology on coronary stents. Bioresorbable scaffolds do not have metal struts and therefore CT-FFR may be performed to evaluate this type of devices [53, 54].

Advanced reconstruction algorithms, such as iterative reconstruction have been introduced in recent years as an alternative to the traditional filtered back projection [78•]. These algorithms focus on reduction of image noise and artifacts. Several trials used iterative reconstruction in combination with sharper kernels and showed improved image quality and detection of in-stent restenosis compared to filtered back projection [79–81]. Photon-counting CT detectors use high-speed semiconductors to directly count the number of incident x-ray photons and measure their energy. One of the potential advantages of this technology is the improved spatial resolution that can be achieved due to smaller detector elements compared to conventional energy-integrating detector systems [59]. In vitro studies have shown that prototype photon-counting CT detectors yield superior in-stent lumen delineation of coronary artery stents compared to conventional energy-integrating arrays [84, 85]. More studies are needed in order to identify the precise role of this technology in the evaluation of coronary stents.

Conclusions

According to the current guidelines, which were published in 2010, the use of CCTA is appropriate for the evaluation of ≥ 3 mm stents when located in the left main coronary artery, in all other cases CCTA is considered either uncertain or inappropriate [82]. As a result of advances in CT technology as well as stent design, the diagnostic performance of CCTA has improved substantially, allowing for better evaluation of smaller stented vessels. However, clinical decisions in patients with angiographic disease benefit assessment of the functional severity. This is particularly relevant after revascularization, when there is a high probability of angiographic stenosis. In the future, CT perfusion imaging or CT-FFR may provide alternative options to established functional tests to guide the management in symptomatic patients with a history of PCI or CABG.

Compliance with Ethical Standards

Conflict of Interest Ayman Jubran declares no conflict of interest.

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Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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• Of importance
•• Of major importance

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